

ACCOMMODATING MIXED-SEVERITY FIRE TO RESTORE AND MAINTAIN ECOSYSTEM INTEGRITY WITH A FOCUS ON THE SIERRA NEVADA OF CALIFORNIA, USA

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ABSTRACT

Existing fire policy encourages the maintenance of ecosystem integrity in fire management, yet this is difficult to implement on lands managed for competing economic, human safety, and air quality concerns. We discuss a fire management approach in the mid-elevations of the Sierra Nevada, California, USA, that may exemplify similar challenges in other fire-adapted regions of the western USA. We also discuss how managing for pyro-

RESUMEN

La política de fuego actual fomenta la permanencia de la integridad del ecosistema en el manejo del fuego. Sin embargo esto es difícil de implementar en tierras manejadas con multiplicidad de objetivos (económicos, de seguridad humana, o relacionados con la calidad del aire). Nosotros debatimos un enfoque sobre el manejo del fuego en las elevaciones medias de la Sierra Nevada en California, EEUU, que podría extenderse a casos similares que ocurren en otras regiones adaptadas al fuego en el oeste de los EEUU. También discutimos como el mane-

diversity through mixed-severity fires can promote ecosystem integrity in Sierran mixed conifer and ponderosa pine (*Pinus ponderosa* Laws) forests. To illustrate, we show how coarse-filter (landscape-level) and complementary fine-filter (species-level) approaches can enhance forest management and conservation biology objectives as related to wildfire management. At the coarse-filter level, pyrodiverse mixed-severity fires provide landscape heterogeneity. Species and ecosystem characteristics associated with pyrodiversity can be maintained or enhanced by accommodating moderately severe fires, which hasten restoration by recreating a complex vegetation mosaic otherwise at risk from suppression. At the fine-filter level, managers can select focal species and species of conservation concern based on the degree to which those species depend on fire and accommodate their specific conservation needs. The black-backed woodpecker (*Picoides arcticus* [Swainson, 1832]) is an ideal focal species for monitoring the ecological integrity of forests restored through mixed-severity fire, and the California spotted owl (*Strix occidentalis occidentalis* [Xantus de Vesey, 1860]) is a species of conservation concern that uses post-fire habitat mosaics and is particularly vulnerable to logging. We suggest a comprehensive approach that integrates wildland fire for ecosystem integrity and species viability with strategic deployment of fire suppression and ecologically based restoration of pyrodiverse landscapes. Our approach would accomplish fire management goals while simultaneously maintaining biodiversity.

jo para lograr la pirodiversidad a través de fuegos de severidad mixta podrían promover la integridad del ecosistema boscoso de coníferas mixtas de estas Sierras y de bosques de pino ponderosa (*Pinus ponderosa* Laws). Para ilustrarlo, mostramos cómo los enfoques a gran escala (a nivel de paisaje) y complementariamente a pequeña escala (a nivel de especie), pueden favorecer los objetivos del manejo forestal y de la conservación biológica en relación al manejo del fuego. A nivel de gran escala, la pirodiversidad de los fuegos de severidad mixta resultó en la heterogeneidad del paisaje. Las características de las especies y del ecosistema asociadas a la pirodiversidad pueden ser mantenidas o favorecidas cuando se admite la ocurrencia de algunos fuegos moderadamente severos, los cuales aceleran la restauración recreando un mosaico complejo de la vegetación, lo que no ocurriría en caso de ser suprimidos. A nivel de pequeña escala, los gestores pueden seleccionar especies focales y especies relacionadas con la conservación, basados en el grado sobre el cual esas especies dependen del fuego y se adaptan a sus necesidades de conservación específicas. El pájaro carpintero negro (*Picoides arcticus* [Swainson, 1832]) es una especie focal ideal para monitorear la integridad ecológica de los bosques restaurados a través de fuegos de severidad mixta, y la lechuza moteada de California (*Strix occidentalis occidentalis* [Xantus de Vesey, 1860]) es una especie de interés para la conservación que utiliza mosaicos de hábitat post fuego y es particularmente vulnerable al aprovechamiento forestal. Nosotros sugerimos un enfoque comprensivo que integre los fuegos naturales para la integridad del ecosistema y la viabilidad de las especies, con la implementación estratégica de la supresión del fuego y la restauración de paisajes pirodiversos basada en principios ecológicos. Nuestro enfoque podría cumplir con los objetivos de manejo del fuego, manteniendo simultáneamente la biodiversidad.

Keywords: coarse filter, ecosystem integrity, fine filter, focal species, mixed-severity fire, pyrodiversity, Sierra Nevada, species of conservation concern

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INTRODUCTION

Pyrodiversity, the mean spatial variability in wildfire effects, results in complex post-fire vegetation mosaics that are associated with high levels of biodiversity. Large fires that produce a variety of severities (i.e., mixed-severity fires) in ponderosa pine (*Pinus ponderosa* Laws) and mixed-conifer forests of the western USA are increasingly recognized for their importance in generating pyrodiverse landscapes (e.g., Perry *et al.* 2011, Williams and Baker 2012, Odion *et al.* 2014, Marcoux *et al.* 2015). Top-down processes such as extreme fire weather, regional climate (which influences fuel moisture and ignitions), and bottom-up processes such as topographic relief, vegetation, and disturbance history govern the distribution and size of fire patches in

mixed-severity fires (Perry *et al.* 2011, Dunn and Bailey 2016). Regional drought, high winds and temperatures, and other factors (e.g., surface fuel loading, crown base height, and crown bulk density; Cruz and Alexander 2010) drive crown fire behavior in these systems, producing small and large patches of high tree mortality within a predominantly surface-fire matrix of mostly surviving trees. Mixed-severity fires therefore generate complex stand structures and landscape heterogeneity—characteristics not typically produced by low-severity fire (Table 1). Low-severity fire, while also important ecologically, is preferred by many managers due to lower risks to economic values. Here, we focus on mixed-severity fires because they have received less attention by managers, but they result in pyrodiverse landscapes (DellaSala and Hanson

Table 1. Pyrodiversity attributes produced by mixed-severity fires associated with high levels of biodiversity and ecosystem functions.

Mixed-severity fire attribute	Ecological importance
Landscape heterogeneity	Habitat for wide array of species—early to late seral associates Mixture of foraging and nesting habitat for spotted owls
Complex stand structures	Biological legacies: large snags, down wood, shrubs, flowering plants Habitat for black-backed woodpeckers
Food web dynamics	Complex trophic structure connected across seral stages with abundant food for certain taxa (e.g., beetle larvae for woodpeckers) Pulsed nutrient inputs (aquatic and terrestrial)
Ecosystem processes	Nutrient cycling and soil nutrient exchange, energy transfer from live to dead material, pollination, predator-prey (owls-mice)
Species composition	Rich and varied, compared to old growth

2015). We demonstrate how ecosystem integrity can be met by managing for pyrodiverse landscapes mediated by mixed-severity fires in the biodiverse region of the Sierra Nevada, California, USA.

Although it is the subject of ongoing research and debate (Odion *et al.* 2016), it has been suggested that mixed conifer, ponderosa pine, and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) forests in this region historically experienced a mix of fire severities, including areas of high overstory tree mortality (DellaSala *et al.* 2014, Stevens *et al.* 2016). There is considerable variability in reported proportions and sizes of high-severity fire patches, with the greatest differences found in relatively smaller study areas or studies in which shorter time periods were analyzed (Table 2). High-severity patches commonly ranged from 0.4 ha to >50 ha, but the historical frequency of patches >1000 ha is still debated (e.g., Baker 2014, Stevens *et al.* 2016). While uncertainty remains on some issues, there is general agreement that most forests of the Sierra Nevada currently have less high-severity fire, in terms of annual or decadal area burned, than they did

historically, prior to fire suppression (Mallek *et al.* 2013, Odion *et al.* 2014, Baker 2015). Additionally, drier low-elevation pine forests burned most frequently at low to moderate severity (Stephens *et al.* 2015), but those fires also contained variably sized high-severity patches (Leiberg 1902, Baker 2014, Hanson and Odion 2016a, b). Douglas-fir (*Pseudotsuga menziesii* Mirbel) (Odion *et al.* 2014) and Sierra lodgepole pine (*Pinus contorta* var. *murrayana* Grev. & Balf.) forests experienced mixed-severity fires as well (Caprio 2008).

Tree mortality is also an important component of mixed-severity fire effects characterized mostly by low-mortality levels (0% to 20% tree basal area), highly variable moderate-mortality levels (20% to 70%), and high-mortality levels (>70% tree mortality) (Perry *et al.* 2011; Figure 1). Agee (2005) noted that mixed-severity fires are not merely an intermediate state between low and high severity but, rather, are a unique type of disturbance that warrants careful study by ecologists.

While there are winners and losers in the immediate aftermath of any disturbance event, the net effect of mixed-severity fire is that it

Table 2. Historical fire severity proportions and maximum high-severity fire patch sizes in mixed-conifer and ponderosa pine forests, Sierra Nevada management region.

Study	Study area size (ha)	Fire severity (%)			Time period (yr)	Maximum high-severity patch size (ha)
		Low	Moderate	High		
Beaty and Taylor (2001) ¹	1 587	1 to 60	14 to 47	6 to 86	43	no data
Bekker and Taylor (2001)	2 042	2 to 4	35 to 44	52 to 63	75	no data
Baker (2014)	330 000	13 to 26	42 to 48	31 to 39	110	9 400
Hanson and Odion (2016a,b)	65 296	no data	no data	22	60	697
Leiberg (1902) ²	1 193 166	no data	no data	20	100	~16 000
Stephens <i>et al.</i> (2015)	11 500	no data	no data	1 to 6	~20 to 30	no data

¹ Fire severity percentages vary by slope position and aspect.

² Does not include high-severity fire patches <32.4 ha, so actual percent high-severity fire would be higher, if patches <32.4 ha had been mapped. Historical high-severity fire mapped polygons are from Leiberg (1902), and analysis of high-severity fire percent by forest type is from Hanson (2007), based on Leiberg (1902).

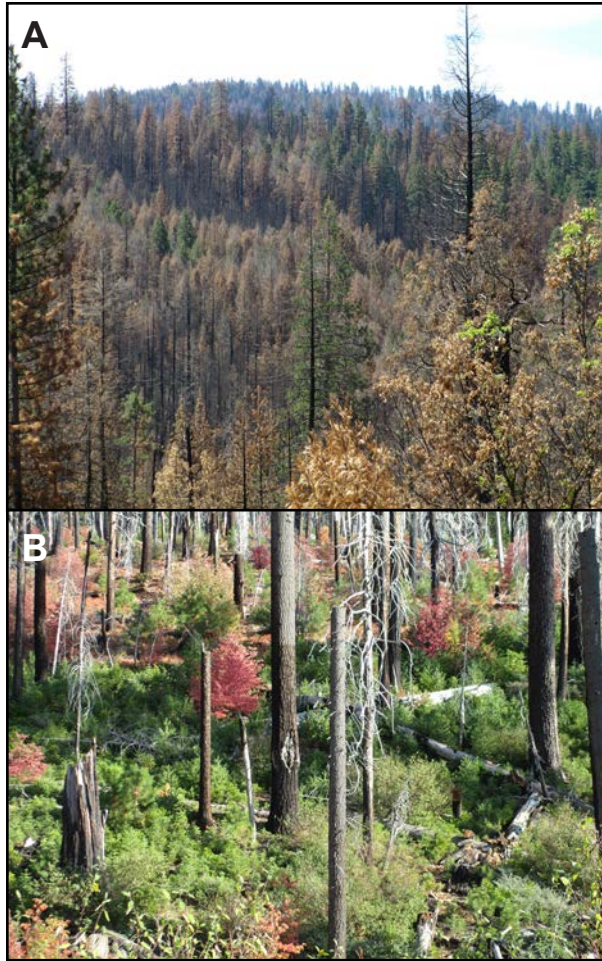


Figure 1. (A) Landscape view of mixed-severity fire effects in the Rim Fire 1 year post fire. The spatial pattern of fire severity patches and patch sizes results in a pyrodiverse landscape that provides habitat for wildlife across a post-fire vegetation gradient of low or unburned vegetation patches to severely burned vegetation patches. (B) Close-up of large patch of complex early seral forest created by high-severity fire in juxtaposition with abundant and varied “biological legacy” trees (complex structures, such as snags, logs, and shrubs that survive fire). Photos by C. Hanson.

provides a mosaic of habitat for a broad suite of species. For instance, songbirds have high levels of species richness and abundance in post-fire vegetation at mid elevations (Fontaine *et al.* 2009, Tingley *et al.* 2016). Black-backed woodpeckers (*Picoides arcticus* [Swainson, 1832]), mountain bluebirds (*Sialia*

currucoides [Bechstein, 1798]), tree swallows (*Tachycineta bicolor* [Vieillot, 1808]), and numerous shrub-nesting birds preferentially use recently burned forests in the Sierra Nevada and other regions, presumably due to increased shrub cover and presence of snags (Fontaine *et al.* 2009, DellaSala *et al.* 2014, Hutto *et al.* 2015, Tingley *et al.* 2016). California spotted owls (*Strix occidentalis occidentalis* [Xantus de Vesey, 1860]) and olive-sided flycatchers (*Contopus cooperi* [Nuttall, 1831]) forage in severely burned patches where prey are abundant, and nest in unburned to moderately burned portions of the same fire mosaic (Bond *et al.* 2009, 2016; Hutto *et al.* 2015; Comfort *et al.* 2016). Bats make use of high snag densities (Buchalski *et al.* 2013) and fire-recruiting plants are associated with severely burned patches (Donato *et al.* 2009). Even mature-forest carnivores such as the Pacific fisher (*Pekania pennanti* [Erxleben, 1777]) actively forage in severely burned patches (Hanson 2015).

The high-severity patches within the mixed-severity mosaic provide a unique pulse of biological legacies—complex structures such as snags, downed logs, and native shrub patches from seed that survive fire and that are important in connecting seral stages through time (Franklin *et al.* 2000, Fontaine *et al.* 2009, Donato *et al.* 2012, DellaSala *et al.* 2014). The economic value of large dead and live trees within these patches means that commercial trees are most often targeted for harvest soon after fire. In addition, nursery-grown young trees are planted soon after fire and, to promote the crop of young trees, herbicides are often sprayed to kill competing vegetation (Lindenmayer *et al.* 2008, 2017). Logging slash from post-fire logging may contribute to subsequent fire behavior (Donato *et al.* 2006, Thompson *et al.* 2007), as can the fuel array of densely planted even-aged trees (Odion *et al.* 2004).

On public lands, current fire policy promotes thinning over large landscapes (e.g.,

USDA Forest Service 2002, US Congress 2003, USDA Forest Service 2009, US Congress 2015), which is costly (Schoennagel and Nelson 2011), infeasible over large areas (Calkin *et al.* 2013, North *et al.* 2015a, Parks *et al.* 2015), and largely ineffective under extreme fire weather conditions (Lydersen *et al.* 2014, Cary *et al.* 2016). For instance, from 2001 to 2008, over 11 million hectares were thinned on national forests (mostly in the western USA) at a cost of more than \$6 billion (Schoennagel and Nelson 2011). Mechanical vegetation treatments can cost over \$3700 per hectare for each round of thinning (Kline 2004), which would need to be repeated at least every 15 to 20 years to keep flammable vegetation at low levels. Additionally, from 1985 to 2015, suppression costs were more than \$25 billion to fight approximately 2 million fires on over 83 million hectares, mostly spent by the Forest Service (Ingalsbee and Raja 2015).

Thus, we concur with others that active management approaches could include more natural fire ignitions (Calkin 2013, Meyer 2015, North *et al.* 2015b) or resource objective wildfires (Meyer 2015) in which fire is put back on the landscape to hasten the process of forest restoration (Moritz *et al.* 2014, Moritz and Knowles 2016). This would also help to meet fire and fuels objectives and allow managers to better accommodate mixed-severity fire effects for ecosystem integrity (Meyer 2015, Dunn and Bailey 2016). We suggest that an ecosystem integrity approach is not inconsistent with current active fuel management on federal lands and may be a cost-effective way to achieve biodiversity goals (North *et al.* 2015b), while reducing some of the conflicts associated with extensive fuels-focused approaches—particularly impacts to imperiled species and at-risk ecosystems. We use the definition of ecosystem integrity common in the literature (e.g., Pimentel *et al.* 2000), also adopted by the USDA Forest Service (2012), as the ability of an ecological system to support and maintain a community of organisms

that has a species composition, diversity, and functional organization comparable to those of natural habitats within a region.

Our focus is the Sierra Nevada region because of national attention given to so many recent fires therein. We include an example of a fire-adapted species (black-backed woodpecker) that uses high-severity patches, and an imperiled species (California spotted owl) known to decline within intensively managed post-fire landscapes. The Sierra Nevada is one of the most diverse temperate conifer forest regions on Earth and has exceptional levels of plant endemism (Ricketts *et al.* 1999). Approximately half of California's 7000 vascular plant species occur in this region, with 400 considered endemic and 200 rare. High levels of vertebrate richness and endemism also occur. Species composition varies across north-south, east-west, and elevational gradients, resulting in high levels of beta diversity.

Importantly, the 2012 forest planning rule (USDA Forest Service 2012) includes specific provisions for managing public resources to maintain or restore: (1) structure, function, composition, and landscape connectivity; (2) ecological conditions for recovery of imperiled and focal species; and (3) rare and unique habitat types (USDA Forest Service 2012). The National Cohesive Wildland Fire Management Strategy (USDI and USDA 2014) and Sierra national parks (e.g., Yosemite, Sequoia and Kings Canyon) also include multi-faceted approaches that promote greater wildfire ignitions. Though national forest lands compose most of the forested area in California, and are thus our focus herein, significant areas of federal forest in California are managed by the National Park Service (NPS), and a state agency, California Department of Forestry and Fire Protection (CAL FIRE), responsible for decisions and operations pertaining to fire suppression on private and state lands. NPS, like the Forest Service, is required to protect species listed under the Endangered Species Act (ESA), and CAL FIRE is subject to the California state ESA. Thus, our approach to wild-

fire management can be applied to these agencies and land ownerships regarding decisions about fire suppression and forest management that might impact imperiled or ESA-listed species associated with post-fire landscapes.

STUDY AREA

The Sierra Nevada management region is a 750 km long, north-south oriented mountain range in California composed of granitic rock, and distributed across three ecoregions: Sierra Nevada proper; portions of the Modoc Plateau; and the eastern portion of the southern Cascades (Bailey 1995; Figure 2). The regional climate is mediterranean with cool, wet winters, and warm, dry summers; precipitation generally decreases west to east and north to south (Millar 1996).

There are 11 national forests totaling about 4.6 million hectares: Modoc, Lassen, Plumas, Tahoe, Eldorado, Stanislaus, Sequoia, Sierra, Inyo, Humboldt-Toiyabe (western portion), and Tahoe Lake Basin Management Unit. Forest planning is governed by the Sierra Nevada Framework (USDA Forest Service 2004), but the Forest Service is currently revising its forest plans for the Inyo, Sequoia, and Sierra national forests as “early adopters” (i.e., first national forests to test the planning rule) of the 2012 forest-planning rule (USDA Forest Service 2012). Three national parks—Lassen, Sequoia and Kings Canyon, and Yosemite—and several large wilderness and inventoried roadless areas >2000 ha also occur in the region.

Coarse-Filter and Fine-Filter Approaches to Ecosystem Integrity in Mixed-Severity Systems

Managers wishing to maintain ecosystem integrity via naturally ignited fires can do so using a combination of coarse- and fine-filter conservation approaches (Noon *et al.* 2003, USDA Forest Service 2012). Coarse filters invariably include relatively few indicators asso-

ciated with the larger ecosystem of interest (e.g., major vegetation types or, in this case, different categories of burn severity). Their presence is meant to indicate that essential components of the whole system are intact, and they operate at broad spatial scales such as those associated with large fires (hundreds of square kilometers). Coarse filters are typically used to guide reserve design based on fundamental principles of conservation biology, including spatially redundant reserve complexes representative of the major forest types and fire severities interconnected across large landscapes. To achieve a pyrodiverse landscape, perhaps the best coarse filter would include high-severity fire patches interspersed with fire refugia (unburned areas) and low- to moderate-severity patches.

Fine-filter considerations complement coarse filters by adding site-specific or habitat elements associated with focal species, guilds, or other species groupings (USDA Forest Service 2012). Application of this kind of filter allows managers to evaluate whether habitat and special conservation needs are met through a given management plan, and ground-truth the utility of burn severity maps by linking mapped fire severities to habitat needs of target species. In addition, the approach allows managers to meet national forest planning requirements to monitor and evaluate a small suite of focal species selected to assess the degree to which ecological conditions are supporting the diversity of plant and animal communities within a given planning area (USDA Forest Service 2012). Focal species can, therefore, be used to monitor the integrity of the larger system to which they belong, and researchers (e.g., Seavy and Alexander 2014, Stephens *et al.* 2015, Siegel *et al.* 2016) have suggested using patterns of plant and animal distributions as a passive management strategy to accommodate mixed-severity systems. The Forest Service also now considers species of conservation concern as “a species, other than federally recognized threat-

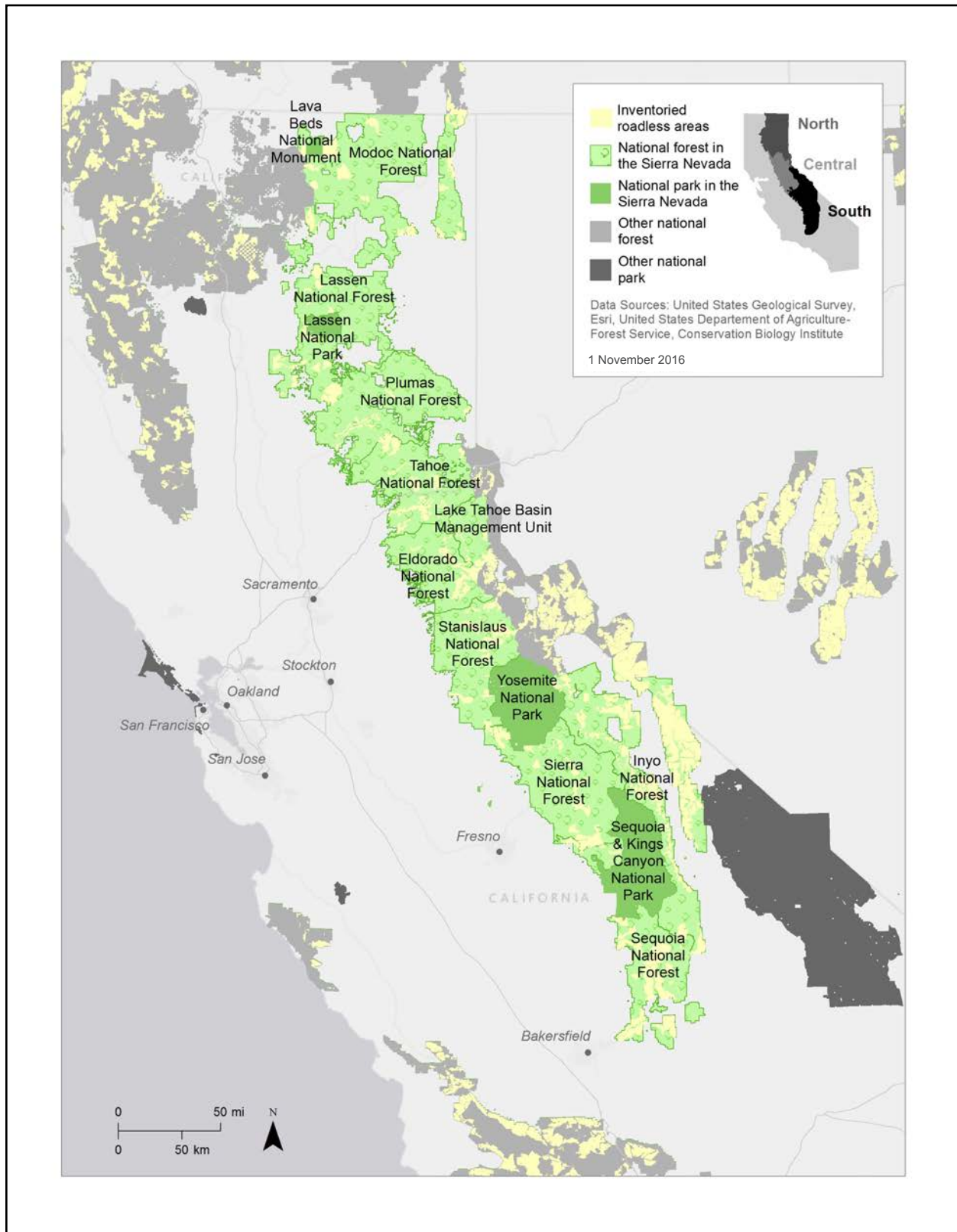


Figure 2. Sierra Nevada study region showing national forests, national parks, and inventoried roadless areas.

ened, endangered, proposed, or candidate species, that is known to occur in the plan area and for which the regional forester has determined that the best available scientific information indicates substantial concern about the species' capability to persist over the long-term in the plan area" (36 CFR 219.9(c); https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5359595.pdf, accessed 12 May 2017). The agency is required to maintain suitable habitat for these species to ensure viable populations are present in the planning area (USDA Forest Service 2012).

Comprehensive Wildland Fire Management

We recognize that land managers face many constraints (legal and social) and often competing regulatory and management objectives that limit wildfire management options. However, the Planning Rule and the National Cohesive Wildland Fire Management Strategy (USDI and USDA 2014) offer opportunities to put more fire back on the landscape whether through prescribed burning or managed wildfires. We provide some general concepts that managers might apply with pyrodiversity outcomes realized through mixed-severity fires that meet ecosystem integrity objectives.

Integrating Wildland Fire and Targeted Fire Suppression (Coarse Filter)

Mixed-severity fire effects for ecosystem benefits can be integrated with targeted suppression and fire-risk reduction efforts near towns using this coarse-filter approach. While we acknowledge that there was concern about the size and severity of the 2013 Rim Fire (Lydersen *et al.* 2014), the largest fire in recent Sierra Nevada history, we note that even this fire produced mostly low- to moderate-severity effects (i.e., ~20% of the burn was high severity based on Monitoring Trends in Burn Severity [MTBS]; http://mtbs.gov/MTBS_Uploads/data/2013/maps/ca3785712008620130817_map.pdf, accessed 23 April 2017), and a wide

range of high-severity patch sizes, which contributed to significant heterogeneity at landscape scales. Thus, we concur with others (e.g., Moritz *et al.* 2014, Ingalsbee and Raja 2015, Dunn and Bailey 2016, Moritz and Knowles 2016, Schoennagel *et al.* 2017) that suppression could be focused narrowly to lands surrounding towns and used in combination with defensible space management nearest homes (Cohen 2000, 2004) so that more wildland fires can burn safely in the backcountry.

Notably, one way to safely modify fire suppression activity would be to restrict large fire crews and heavy equipment to protect homes and communities within the Wildland Urban Interface (WUI). The WUI is usually considered to extend to ~2 km from an at-risk community (US Congress 2003, USDA Forest Service 2004), even though most vegetation treatments are conducted farther from communities (Schoennagel *et al.* 2009). Beyond the WUI, point protection strategies would be used to keep fire away from isolated structures and infrastructures like cabins, communication towers, bridges, or other human assets that could be destroyed by fire. Relatively small, mobile fire crews would also use minimum impact suppression tactics (i.e., Minimum Impact Suppression Tactics [MIST]; <https://www.nifc.gov/PUBLICATIONS/redbook/2003/AppendixU.pdf>, accessed 12 May 2107) in backcountry areas, primarily monitoring fire spread but, when necessary, actively managing it (rather than containing and controlling wildfire as in traditional full-suppression strategies) by steering fire away from threatened social assets (Donovan and Brown 2005, 2008; Ingalsbee and Raja 2015). In municipal watersheds where fire management plans may want to avoid high-severity fires burning near water sources, more fires could be allowed to burn during moderate weather conditions. Wildfire management should be a useful tool for managing fuel loads in municipal watersheds where the use of chemicals or heavy equipment for either thinning or suppression would cause unacceptable impacts to water quality

and soils. MIST could also be employed where fires in wilderness and roadless complexes, national parks, and even in roaded areas many kilometers from the nearest town pose low risk to residential areas. In sum, this approach would shift wildfire operations from limiting fire spread, size, or duration in back-country areas to working with fire for ecosystem benefits while still effectively providing for community wildfire protection.

Sierra Nevada national forests and parks are large enough to accommodate most large fires over thousands or even tens of thousands of hectares (Appendix 1). For instance, many (>50%) of the largest forest fires from 1984 to 2014 were primarily contained within an individual national forest or national park boundary. In general, federal lands offer unique opportunities in which the maintenance of pyrodiversity for biodiversity could be emphasized in large protected areas (wilderness and roadless area complexes; Appendix 2). Coordination among agencies with similar objectives may allow for more naturally ignited fires over mixed ownerships having similar objectives (e.g., wilderness or roadless areas, other remote forests, conservation areas juxtaposed with parks) using an all-lands approach. If reserves were too small to accommodate large fires or patches of different fire severities, then complexes of multiple reserves widely distributed across a region in redundant locations would collectively help maintain the full complement of post-fire stages using the coarse-filter approach.

In the Sierra Nevada, the draft revised forest plans for the three early-adopter national forests in the southern portion of the range have included a fire-management-zoning approach similar to what we suggest here, allowing more naturally ignited fire in remote areas and suppressing fires close to communities (USDA Forest Service 2016). However, the focus in the draft plans remains on mechanical thinning and post-fire logging (USDA Forest Service 2016). We submit that an approach that allows more natural fire ignitions is advis-

able and warranted from the standpoint of both ecosystem integrity and public safety, as discussed herein.

Focal Species and Species of Conservation Concern (Fine Filter)

By way of example, we consider two species that could be used to monitor mixed-severity effects. The black-backed woodpecker would be an ideal focal species given its very close association with high-severity fire patches, as would the California spotted owl, a species of conservation concern. Both species are complementary to mixed-severity fire management, given that the woodpecker is mainly associated with the high-severity component, and spotted owls use a broad gradient of fire severity patches. Moreover, while there is some overlap in geographic ranges, spotted owls generally occupy low- to mid-montane forests, while the black-backed woodpecker lives in mid- to high-elevation mixed-conifer forests up to subalpine forests.

Black-backed woodpecker as focal species of high-severity fire patches. In the Sierra Nevada, black-backed woodpeckers occur across mid- to upper-montane and subalpine conifer forests from ~1200 m to 2800 m, depending on latitude. While still uncommon even in burned areas, the greatest concentrations occur in severely burned, mixed-conifer and upper montane forests with high basal area of snags (Hanson and North 2008, Saracco *et al.* 2011) where wood-boring beetle larvae are abundant (Saab *et al.* 2007). Burned areas also typically harbor high densities of medium to large dead trees >30 cm dbh (Cahall and Hayes 2009, Saab *et al.* 2009, Tingley *et al.* 2014). Black-backed woodpeckers also occur (albeit much more rarely) in dense, mature unburned forests (Bonnot *et al.* 2009, Fogg *et al.* 2014) where they have relatively larger home ranges, presumably reflecting conditions that are less than optimal (Tingley *et al.* 2014). Nevertheless, unburned forests with high levels of dead trees

from drought and native bark beetles might at least slow the rate of population decline during interludes between severe fires (Rota *et al.* 2014). Only a small fraction of fires burn suitable woodpecker habitat, due to the narrow convergence of conditions that include recent (generally ≤ 8 years post-fire) higher-severity fire effects in dense, mature, middle- to high-elevation conifer forest (Casas *et al.* 2016). Often a single pair of birds uses hundreds of hectares (Dudley and Saab 2007, Tingley *et al.* 2014).

Black-backed woodpeckers are vulnerable to even partial post-fire logging (Hutto and Gallo 2006, Koivula and Schmiegelow 2007, Saab *et al.* 2009, Rost *et al.* 2013). Radio-telemetry studies in the Lassen and Plumas national forests of California showed that home-range sizes were significantly larger in forests in which some post-fire logging occurred, and post-fire logged patches in the Sierra Nevada were avoided (Tingley *et al.* 2014). For example, even though post-fire logging was proposed for what seems like a minor portion of the King Fire, logging was especially concentrated within the highest quality woodpecker habitat (Figure 3), where a high density of medium to large snags occurred. Notably, on national forests of the Sierra Nevada, post-fire logging decisions have typically authorized removal of 40% to 60% of high-severity patches, displacing complex early seral forest with tree plantations (e.g., USDA Forest Service 2014, 2015, 2016). Retention of dead trees in logging units generally averages ~ 10 trees per hectare >38 cm dbh (USDA Forest Service 2004). By comparison, to maintain habitat for this focal species, generally hundreds of medium to large snags per hectare (>30 cm dbh to 40 cm dbh, and especially snags >50 cm dbh) are needed (Hanson and North 2008, Saab *et al.* 2009, Tingley *et al.* 2014) in patches consistent with home-range size, along with an ample supply of dense, mature or old conifer forest to facilitate conditions for high quality habitat when fires do occur (DellaSala *et al.* 2014).

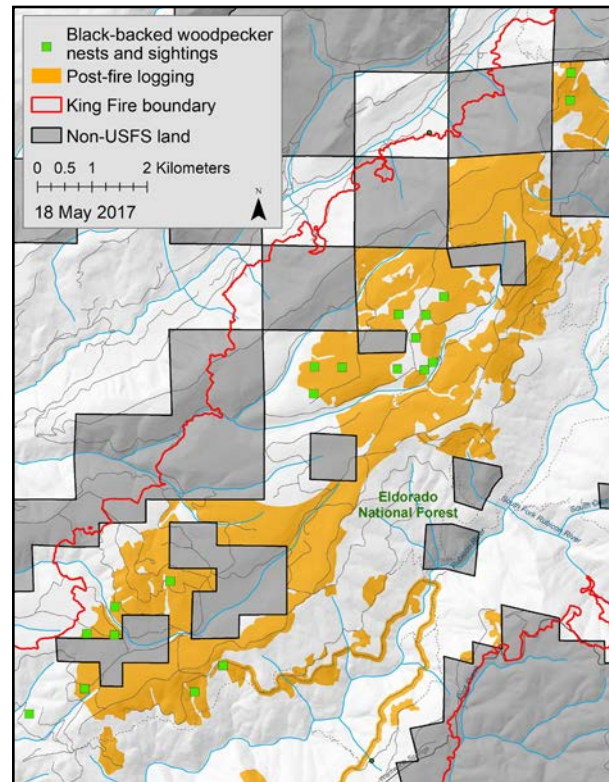


Figure 3. King Fire logging units on the Eldorado National Forest and black-backed woodpecker nests and sightings. After extensive surveys for black-backed woodpeckers were conducted for the US Forest Service throughout the fire area one year post fire, using playback recordings to detect the birds, all but one of the detections was in a relatively small area of dense, mature mid-montane conifer forest in a very large high-severity fire patch in the northern portion of the fire area (shown above). The Forest Service’s decision authorized post-fire logging of $\sim 80\%$ of these locations.

California spotted owl as species of conservation concern. Early studies on habitat associations and reproductive success of spotted owls in the Sierra Nevada were conducted in long-unburned forests, and “non-suitable” owl habitat was typically the result of logging (e.g., Moen and Gutiérrez 1997, Blakesley *et al.* 2005). Because spotted owls are usually associated with older, dense forests, it was assumed that effects of high-severity wildfires were similar to logging (Weatherspoon *et al.* 1992). However, recent studies have demon-

strated that occupancy (Roberts *et al.* 2011, Lee *et al.* 2012, Lee and Bond 2015a) and reproductive success (Roberts 2008, Lee and Bond 2015b) were similar or higher in forests burned with a mixture of fire severities compared to long-unburned forests for up to at least 15 years post fire (longer-term studies have not been conducted). Lee and Bond (2015a) reported higher occupancy rates than any Sierra Nevada study area for historical owl breeding sites one year after the Rim Fire. The amount of high-severity fire within an owl pair's 120 ha protected activity center, as defined by the Forest Service, had no effect on occupancy, although occupancy by single owls declined slightly as the extent of severe-fire patches increased.

Thus, even though spotted owls are not considered a fire-dependent species, they do persist after mixed-severity fires when both unburned and severely burned patches occur within historical territories (Lee *et al.* 2012; Lee and Bond 2015a, b). Owls foraged preferentially in high-severity patches within mature forest in the southern Sierra Nevada (Bond *et al.* 2009) and used high- and moderate-severity patches in the San Bernardino Mountains in proportion to availability (Bond *et al.* 2016). Notably, structural complexity (including high density of dead trees) is important for spotted owl foraging habitat. Bond *et al.* (2009) found that dead tree basal area and shrub cover were highest in high-severity fire patches in which owls preferentially foraged. The owls found a rich food source, in the form of small mammal prey, in post-fire habitat (Bond *et al.* 2016). California spotted owls also selected high-severity patches for foraging more than any other fire severity condition or than long-unburned forests when within 1.5 km of the nest or roost (Figures 4 and 5). Although there are reports of California spotted owls nesting in moderate-severity patches, these raptors mostly nest and roost in long-unburned or lower-severity areas within a burned landscape (Bond *et al.* 2009), underscoring the importance of

the mixed-severity mosaic. In contrast, Jones *et al.* (2016) found higher rates of territory extirpation and lower rates of colonization of owl sites that experienced >50% high-severity fire in the King Fire on the Eldorado National Forest, and reported avoidance of high-severity patches for foraging. The circumstances of their study differed greatly from others (Lee and Bond 2015a, b), presumably due to pre- and post-fire logging within owl territories, as well as extensive high-severity fire in pre-fire clearcuts with young plantations.

Long-term occupancy monitoring without the confounding influence of post-fire logging is especially important to understanding fire effects on spotted owls. Hence, Bond *et al.* (2009) recommend that, if managers want to maintain spotted owl habitat after fire, they should prohibit post-fire logging and pesticide and herbicide applications within at least 1.5 km of historical spotted owl nest and roost sites. Even larger areas may be needed given that owl breeding-season home ranges can extend upwards of 700 ha (Bond *et al.* 2016), and some birds expand their range or migrate during the non-breeding season (Bond *et al.* 2010). Therefore, a reasonable protected area might be within 2.4 km of nest and roost sites, which corresponds to interim spotted owl management guidelines of the Forest Service's Pacific Southwest Research Station (http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd504726.pdf).

Restoration of Degraded Forests

Land-use stressors that degrade or impair ecosystem processes are fundamentally at odds with ecosystem integrity approaches (Pimentel *et al.* 2000, USDA Forest Service 2012). Thus, restoration treatments can be used to reverse the causative agents of ecosystem degradation. One example is to limit human-set fires via: (1) seasonal closure and decommissioning of roads, or convert roads not considered essential in firefighting within the

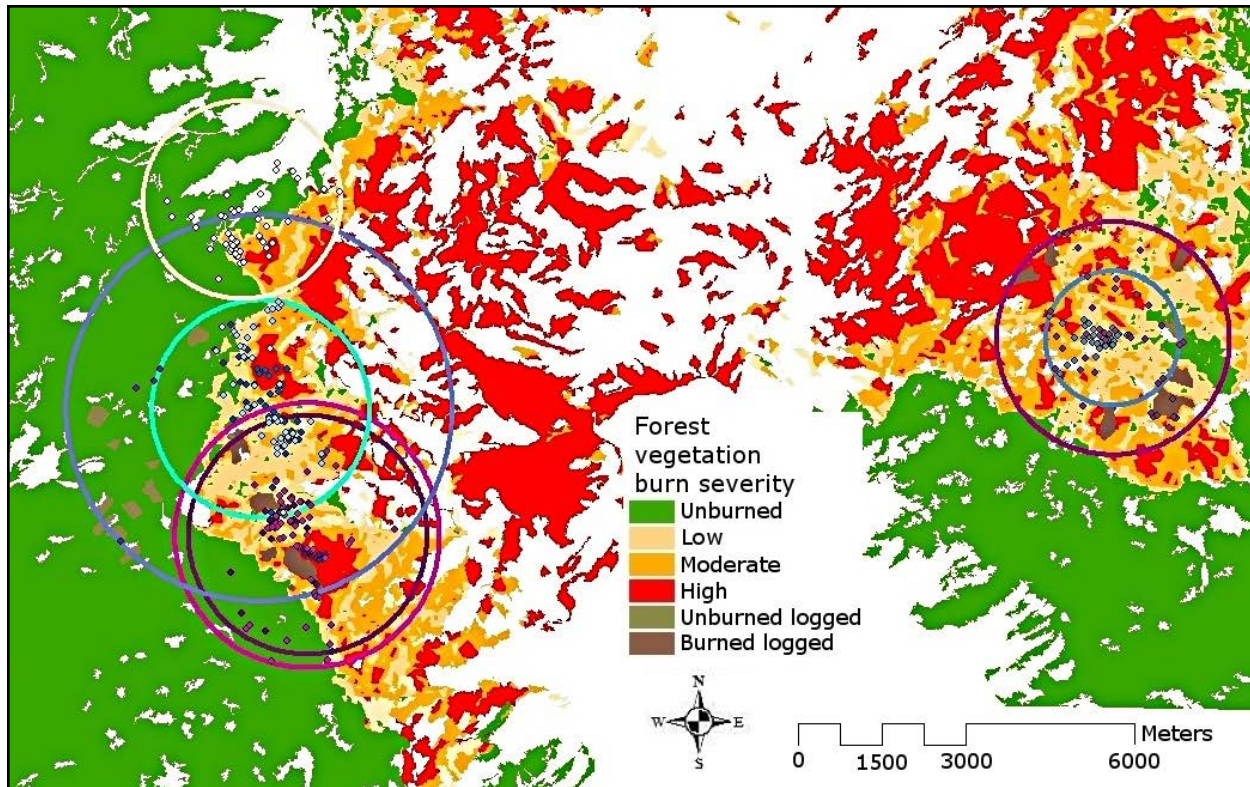


Figure 4. (A) Estimated foraging locations (obtained in 2006) of seven radio-marked California spotted owls in the 2002 McNally Fire, Sequoia National Forest, Sierra Nevada, USA. Different colored points represent each individual owl's estimated foraging location. Circles represent foraging ranges: each circle is centered on the nest with its radius extending to the farthest estimated foraging location for each individual owl. White areas are non-suitable for owls (e.g., foothill chaparral vegetation).

WUI to indefinitely closed; and (2) focused thinning and prescribed burning nearest homes, around campgrounds and other facilities, and along narrowly defined road prisms close to towns to avoid fire spread from anthropogenic ignitions. Managers could also concentrate thinning of small trees (shaded fuel breaks) along with prescribed burning nearest critical evacuation routes for communities with only one means of ingress or egress, redesign traveler stopping points along roads to avoid fire-prone settings, and concentrate visitation in fire-safe locations. Importantly, because tree plantations create unnaturally homogenized forests that lack complex structures, managers could integrate thinning with mixed-intensity prescribed burning, or naturally ignited fires, and create snags and downed logs to introduce structural complexi-

ty. Thinning small trees combined with prescribed fire (Kalies and Kent 2016) may reduce fire intensity in densely stocked tree plantations (Odion *et al.* 2004).

CONCLUSIONS

The 2012 Planning Rule provides the Forest Service with new direction for restoring and maintaining integrity and for managing focal species and species of conservation concern that can be integrated with fuels management approaches. The National Cohesive Wildland Fire Management Strategy (USDI and USDA 2014) allows managing wildfire for ecosystem benefits; hence, our findings can be applied to Department of Interior lands as well.

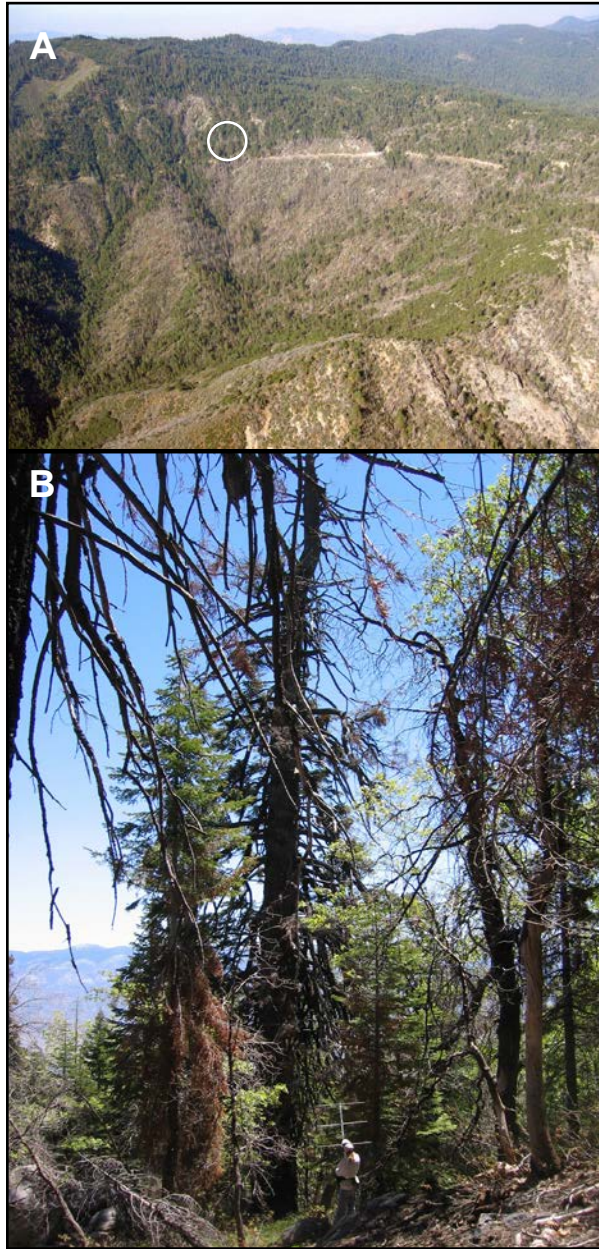


Figure 5. (A) General location of a California spotted owl nest territory in the 2002 McNally Fire (circle not to scale). Nest site was in a low-severity patch directly adjacent to high-severity patch (severity defined using Miller and Thode 2007). (B) Zoom-in (center snag) of general location of California spotted owl nest tree within McNally Fire burn patch shown in (A). Photos by M. Bond.

We suggest that managing for ecosystem integrity using both a coarse- and fine-filter approach centered on pyrodiverse fire effects

can inform forest management in a biodiversity context. Our approach would have the added benefit of likely reducing suppression costs and some of the negative effects of mechanical vegetation removal over large areas (Dale 2006, Donovan and Brown 2008, Dunn and Bailey 2016). The complementary nature of conservation filters would allow managers to check burn severity maps with habitat associations of focal species to assess management efficacy.

Managers face substantial political and public pressure to suppress fires through the use of aggressive firefighting tactics, but such tactics do little to contain fires under extreme weather conditions (Lydersen *et al.* 2014, Moritz *et al.* 2014, Ingalsbee and Raja 2015, Carey *et al.* 2016). Instead, managers could be encouraged to use prescribed and naturally ignited fires that yield both cost savings and ecosystem benefits. Unfortunately, federal fire suppression budgets are dominated by suppression costs, causing siphoning of funds away from other essential programs (Ingalsbee and Raja 2015). To support managers in using more natural fire ignitions, conditions and certain trigger points could be more clearly defined and integrated with forest planning. This would allow flexibility to use several approaches to managing a fire, even on the same incident. Thus, in theory, a large fire could be managed in one area with general containment strategies that employ MIST (backcountry), while simultaneously in another area (near towns) with direct attack methods.

Accommodating mixed-severity fires for ecosystem benefits pertains to both ends of the fire continuum: large fires with high-severity effects that generate unique biological pulses (e.g., complex structures), and lower-severity systems that may have been homogenized through management and suppression. This suggests an important opportunity for expanding fire management beyond traditional kinds of prescribed burning to include prescriptions that benefit a broader suite of species associated with pyrodiverse landscapes (Moritz *et al.*

2014, DellaSala and Hanson 2015, Moritz and Knowles 2016). We note the conundrum of natural fire ignitions creating greater smoke emissions that may conflict with air quality objectives. Importantly, the Environmental Protection Agency (2016) recently revised policies to provide special regulatory exemptions and provisions that allow for more managed wildfires.

With proper planning and use of modern smoke management techniques, adverse effects of emissions on public health can be mitigated and fire restoration goals better accommodated. However, smoke emissions must be viewed as an unavoidable trade-off to be weighed against other potentially worse effects from attempted fire exclusion (that will eventually burn in a wildfire) or other chemical and mechanical methods for managing fuel loads that have ecosystem consequences.

There is clearly a need for research on whether natural fire ignitions can primarily provide desired mixed-severity fire effects. We suggest that studies are needed to determine the following.

- (1) Specific locations and forest types best suited for mixed-severity fire effects, particularly in relation to ecological mechanisms by which pyrodiversity influences biodiversity.
- (2) Current versus historical sizes and proportions of fire-severity patches and how those might be affected by climate change.

- (3) Additional species that may be affected by suppression such as declining shrub-nesting birds associated with complex early-seral forests (Hanson 2014).
- (4) Importance of other disturbance events (e.g., native insect outbreaks, drought) in maintaining ecosystem integrity.
- (5) Effects of mechanical treatments before and after fire on the integrity and quality of mixed-severity patches including species of conservation concern and focal species.
- (6) Kinds of education efforts required to implement this type of integrated disturbance ecology approach.
- (7) Decision-support tools to help managers assess the costs and benefits of natural fire ignitions, along with conditions under which fires should be suppressed for human safety.

We argue that expanding natural fire ignitions for ecosystem benefits in combination with strategic use of defensible space, directed suppression, and active fuels management in appropriate areas provide untapped potential to enhance ecosystem integrity while protecting people and infrastructure with the potential for lower financial costs. Our approach is based on an ecological understanding of the importance of mixed-severity fires (DellaSala and Hanson 2015), and the need to reconsider “catastrophe” biases regarding natural disturbance processes (Lindenmayer *et al.* 2017).

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LITERATURE CITED

- Agee, J.K. 2005. The complex nature of mixed severity fire regimes. Pages 1–10 in: L. Taylor, J. Zelnik, S. Cadwallader, and B. Hughes, editors. Mixed severity fire regimes: ecology and management symposium proceedings. Volume AFE MISC03, Washington State University Cooperative Extension Service and Association for Fire Ecology, Spokane, Washington, USA.
- Bailey, R.G. 1995. Description of the ecoregions of the United States. Miscellaneous Publication 1391, USDA Forest Service, Washington, D.C., USA.
- Baker, W.L. 2014. Historical forest structure and fire in Sierran mixed-conifer forests reconstructed from General Land Office survey data. *Ecosphere* 5(7): 1–70. doi: [10.1890/ES14-00046.1](https://doi.org/10.1890/ES14-00046.1)
- Baker, W.L. 2015. Are high-severity fires burning at much higher rates recently than historically in dry-forest landscapes of the western USA? *PLoS ONE* 10(9): e0136147. doi: [10.1371/journal.pone.0136147](https://doi.org/10.1371/journal.pone.0136147)
- Beaty, R.M., and A.H. Taylor. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, southern Cascades, USA. *Journal of Biogeography* 28: 955–966. doi: [10.1046/j.1365-2699.2001.00591.x](https://doi.org/10.1046/j.1365-2699.2001.00591.x)
- Bekker, M.F., and A.H. Taylor. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. *Plant Ecology* 155: 15–28. doi: [10.1023/A:1013263212092](https://doi.org/10.1023/A:1013263212092)
- Blakesley, J.A., B.R. Noon, and D.R. Anderson. 2005. Site occupancy, apparent survival, and reproduction of California spotted owls in relation to forest stand characteristics. *Journal of Wildlife Management* 69: 1554–1564. doi: [10.2193/0022-541X\(2005\)69\[1554:SOASAR\]2.0.CO;2](https://doi.org/10.2193/0022-541X(2005)69[1554:SOASAR]2.0.CO;2)
- Bond, M.L., D.E. Lee, R.B. Siegel, and J.P. Ward. 2009. Habitat use and selection by California spotted owls in a postfire landscape. *Journal of Wildlife Management* 73: 1116–1124. doi: [10.2193/2008-248](https://doi.org/10.2193/2008-248)
- Bond, M.L., D.E. Lee, and R.B. Siegel. 2010. Winter movements by California spotted owls in a burned landscape. *Western Birds* 41: 174–180.
- Bond, M.L., C. Bradley, and D.E. Lee. 2016. Foraging habitat selection by California spotted owls after fire. *Journal of Wildlife Management* 80: 1290–1300. doi: [10.1002/jwmg.21112](https://doi.org/10.1002/jwmg.21112)
- Bonnot, T.W., J.J. Millspaugh, and M.A. Rumble. 2009. Multi-scale nest-site selection by black-backed woodpeckers in outbreaks of mountain pine beetles. *Forest Ecology and Management* 259: 220–228. doi: [10.1016/j.foreco.2009.10.021](https://doi.org/10.1016/j.foreco.2009.10.021)
- Buchalski, M.R., J.B. Fontaine, P.A. Heady III, J.P. Hayes, and W.F. Frick. 2013. Bat response to differing fire severity in mixed-conifer forest, California, USA. *PLOS ONE* 8(3): e57884. doi: [10.1371/journal.pone.0057884](https://doi.org/10.1371/journal.pone.0057884)
- Cahall, R.E., and J.P. Hayes. 2009. Influences of postfire salvage logging on forest birds in the eastern Cascades, Oregon, USA. *Forest Ecology and Management* 257: 1119–1128. doi: [10.1016/j.foreco.2008.11.019](https://doi.org/10.1016/j.foreco.2008.11.019)
- Calkin, D.E., J.D. Cohen, M.A. Finney, and M.P. Thompson. 2013. How fire risk management can prevent future wildfire disasters in the wildland-urban interface. *PNAS* 111(2): 746–751. doi: [10.1073/pnas.1315088111](https://doi.org/10.1073/pnas.1315088111)
- Caprio, A.C. 2008. Reconstructing fire history of lodgepole pine on Chagoopa Plateau, Sequoia National Park, California. USDA Forest Service General Technical Report PSW-GTR-189, Pacific Southwest Research Station, Riverside, California, USA.

- Cary, G.J., I.D. Davies, R.A. Bradstock, R.E. Keane, and M.D. Flannigan. 2016. Importance of fuel treatment for limiting moderate-to-high intensity fire: findings from comparative fire modelling. *Landscape Ecology* (2016): 1–11. doi: [10.1007/s10980-016-0420-8](https://doi.org/10.1007/s10980-016-0420-8)
- Cohen, J.D. 2000. Preventing disaster: home ignitability in the wildland-urban interface. *Journal of Forestry* 98: 15–21.
- Cohen, J.D. 2004. Relating flame radiation to home ignition using modeling and experimental crown fires. *Canadian Journal of Forest Resources* 34: 1616–1626. doi: [10.1139/x04-049](https://doi.org/10.1139/x04-049)
- Comfort, E.J., D.A. Clark, R.G. Anthony, J. Bailey, and M.G. Betts. 2016. Quantifying edges as gradients at multiple scales improves habitat selection models for northern spotted owl. *Landscape Ecology* (2016)31: 1227–1240. doi: [10.1007/s10980-015-0330-1](https://doi.org/10.1007/s10980-015-0330-1)
- Cruz M.G., and M.E. Alexander. 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *International Journal of Wildland Fire* 19: 377–398. doi: [10.1071/WF08132](https://doi.org/10.1071/WF08132)
- Dale, L. 2006. Wildfire policy and fire use on public lands in the United States. *Society and Natural Resources* 19: 275–284. doi: [10.1080/08941920500460898](https://doi.org/10.1080/08941920500460898)
- DellaSala, D.A., and C.T. Hanson, editors. 2015. *The ecological importance of mixed-severity fires: nature's phoenix*. Elsevier, New York, New York, USA.
- DellaSala, D.A., M.L. Bond, C.T. Hanson, R.L. Hutto, and D.C. Odion. 2014. Complex early seral forests of the Sierra Nevada: what are they and how can they be managed for ecological integrity? *Natural Areas Journal* 34: 310–324. doi: [10.3375/043.034.0317](https://doi.org/10.3375/043.034.0317)
- Donato, D.C., J.B. Fontaine, J.L. Campbell, W.D. Robinson, J.B. Kauffman, and B.E. Law. 2006. Post-wildfire logging hinders regeneration and increases fire risk. *Science* 311: 352. doi: [10.1126/science.1122855](https://doi.org/10.1126/science.1122855)
- Donato, D.C., J.B. Fontaine, W.D. Robinson, J.B. Kauffman, and B.E. Law. 2009. Vegetation response to a short interval between high-severity wildfires in a mixed-evergreen forest. *Journal of Ecology* 97: 142–154. doi: [10.1111/j.1365-2745.2008.01456.x](https://doi.org/10.1111/j.1365-2745.2008.01456.x)
- Donato, D.C., J.L. Campbell, and J.F. Franklin. 2012. Multiple successional pathways and precocity in forest development: can some forests be born complex? *Journal of Vegetation Science* 23(3): 576–584. doi: [10.1111/j.1654-1103.2011.01362.x](https://doi.org/10.1111/j.1654-1103.2011.01362.x)
- Donovan, G.H., and T.C. Brown. 2005. An alternative incentive structure for wildfire management on national forest land. *Forest Science* 51: 387–395.
- Donovan, G.H., and T.C. Brown. 2008. Estimating the avoided fuel-treatment costs of wildfire. *Western Journal of Applied Forestry* 23: 197–201.
- Dudley, J.G., and V.A. Saab. 2007. Home range size of black-backed woodpeckers in burned forests of southwestern Idaho. *Western North American Naturalist* 67: 593–600. doi: [10.3398/1527-0904\(2007\)67\[593:HRSOBW\]2.0.CO;2](https://doi.org/10.3398/1527-0904(2007)67[593:HRSOBW]2.0.CO;2)
- Dunn, C.J., and J.D. Bailey. 2016. Tree mortality and structural change following mixed-severity fire in *Pseudotsuga* forests of Oregon's western Cascades, USA. *Forest Ecology and Management* 365: 107–118. doi: [10.1016/j.foreco.2016.01.031](https://doi.org/10.1016/j.foreco.2016.01.031)
- Environmental Protection Agency. 2016. Final rule: treatment of data influenced by exceptional events. 40 CFR parts 50 and 51. Federal Register volume 81, issue 191, October 3, 2016. US Government Publishing Office, Washington, D.C., USA.
- Fogg, A.M., L.J. Roberts, and R.D. Burnett. 2014. Occurrence patterns of black-backed woodpeckers in green forest of the Sierra Nevada Mountains, California, USA. *Avian Conservation and Ecology* 9(2): Article 3. doi: [10.5751/ACE-00671-090203](https://doi.org/10.5751/ACE-00671-090203)

- Fontaine, J.B., D.C. Donato, W.D. Robinson, B.E. Law, and J.B. Kauffman. 2009. Bird communities following high-severity fire: response to single and repeat fires in a mixed-evergreen forest, Oregon, USA. *Forest Ecology and Management* 257: 1496–1504. doi: [10.1016/j.foreco.2008.12.030](https://doi.org/10.1016/j.foreco.2008.12.030)
- Franklin, J.F., D. Lindenmayer, J.A. MacMahon, A. McKee, J. Magnuson, D.A. Perry, R. Waide, and D. Foster. 2000. Threads of continuity. *Conservation Biology in Practice* 1: 8–16. doi: [10.1111/j.1526-4629.2000.tb00155.x](https://doi.org/10.1111/j.1526-4629.2000.tb00155.x)
- Hanson, C.T. 2014. Conservation concerns for Sierra Nevada birds associated with high-severity fire. *Western Birds* 45: 204–212.
- Hanson, C.T. 2015. Use of higher severity fire areas by female Pacific fishers on the Kern Plateau, Sierra Nevada, California, USA. *Wildlife Society Bulletin* 39: 497–502. doi: [10.1002/wsb.560](https://doi.org/10.1002/wsb.560)
- Hanson, C.T., and M.P. North. 2008. Postfire woodpecker foraging in salvage-logged and unlogged forests of the Sierra Nevada. *Condor* 110: 777–782. doi: [10.1525/cond.2008.8611](https://doi.org/10.1525/cond.2008.8611)
- Hanson, C.T., and D.C. Odion. 2016a. Historical forest conditions within the range of the Pacific fisher and spotted owl in the central and southern Sierra Nevada, California, USA. *Natural Areas Journal* 36: 8–19. doi: [10.3375/043.036.0106](https://doi.org/10.3375/043.036.0106)
- Hanson, C.T., and D.C. Odion. 2016b. A response to Collins, Miller, and Stephens. *Natural Areas Journal* 36: 229–233.
- Hessburg, P.F., D.J. Churchill, A.J. Larson, R.D. Haugo, C. Miller, T.A. Spies, M.P. North, N.A. Povak, R.T. Belote, P.H. Singleton, W.L. Gaines, R.E. Keane, G.H. Aplet, S.L. Stephens, P. Morgan, P.A. Bisson, B.E. Rieman, R.B. Salter, and G.H. Reeves. 2015. Restoring fire-prone inland Pacific landscapes: seven core principles. *Landscape Ecology* 30: 1805–1835. doi: [10.1007/s10980-015-0218-0](https://doi.org/10.1007/s10980-015-0218-0)
- Hessburg, P.F., T.A. Spies, D.A. Perry, C.N. Skinner, A.H. Taylor, P.M. Brown, S.L. Stephens, A.J. Larson, D.J. Churchill, N.A. Povak, P.H. Singleton, B. McComb, W.J. Zielinski, B.M. Collins, R.B. Salter, J.J. Keane, J.F. Franklin, and G. Riegel. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and northern California. *Forest Ecology and Management* 366: 221–250. doi: [10.1016/j.foreco.2016.01.034](https://doi.org/10.1016/j.foreco.2016.01.034)
- Hutto, R.L., and S.M. Gallo. 2006. The effects of postfire salvage logging on cavity-nesting birds. *Condor* 108: 817–831. doi: [10.1650/0010-5422\(2006\)108\[817:TEOPSL\]2.0.CO;2](https://doi.org/10.1650/0010-5422(2006)108[817:TEOPSL]2.0.CO;2)
- Hutto, R.L., M.L. Bond, and D.A. DellaSala. 2015. Using bird ecology to learn about the benefits of severe fire. Pages 55–88 in: D.A. DellaSala and C.T. Hanson, editors. *The ecological importance of mixed-severity fires: nature's phoenix*. Elsevier, New York, New York, USA. doi: [10.1016/B978-0-12-802749-3.00003-7](https://doi.org/10.1016/B978-0-12-802749-3.00003-7)
- Ingalsbee, T., and U. Raja. 2015. The rising costs of wildfire suppression and the case for ecological fire use. Pages 348–371 in: D.A. DellaSala and C.T. Hanson, editors. *The ecological importance of mixed-severity fires: nature's phoenix*. Elsevier, New York, New York, USA. doi: [10.1016/B978-0-12-802749-3.00012-8](https://doi.org/10.1016/B978-0-12-802749-3.00012-8)
- Jones, G.M., R.J. Gutierrez, D.J. Tempel, S.A. Whitmore, W.J. Berigan, and M.Z. Peery. 2016. Megafires: an emerging threat to old-forest species. *Frontiers in Ecology and the Environment* 14: 300–306. doi: [10.1002/fee.1298](https://doi.org/10.1002/fee.1298)
- Kalies, E.L., and L.L.Y. Kent. 2016. Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management* 375: 84–95. doi: [10.1016/j.foreco.2016.05.021](https://doi.org/10.1016/j.foreco.2016.05.021)

- Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation's forests. USDA Forest Service Pacific Northwest Research Stations PNW-RN-542. <http://www.fs.fed.us/pnw/pubs/pnw_rn542.pdf>. Accessed 2 February 2017.
- Koivula, M.J., and F.K.A. Schmiegelow. 2007. Boreal woodpecker assemblages in recently burned forested landscapes in Alberta, Canada: effects of post-fire harvesting and burn severity. *Forest Ecology and Management* 242: 606–618. doi: [10.1016/j.foreco.2007.01.075](https://doi.org/10.1016/j.foreco.2007.01.075)
- Lee, D.E., and M.L. Bond. 2015a. Previous year's reproductive state affects spotted owl site occupancy and reproduction responses to natural and anthropogenic disturbances. *Condor* 117: 307–319. doi: [10.1650/CONDOR-14-197.1](https://doi.org/10.1650/CONDOR-14-197.1)
- Lee, D.E., and M.L. Bond. 2015b. Occupancy of California spotted owl sites following a large fire in the Sierra Nevada. *Condor* 117: 228–236. doi: [10.1650/CONDOR-14-155.1](https://doi.org/10.1650/CONDOR-14-155.1)
- Lee, D.E., M.L. Bond, and R.B. Siegel. 2012. Dynamics of breeding-season site occupancy of the California spotted owl in burned forests. *Condor* 114: 792–802. doi: [10.1525/cond.2012.110147](https://doi.org/10.1525/cond.2012.110147)
- Leiberg, J.B. 1902. Forest conditions in the northern Sierra Nevada, California. USDI Geological Survey Professional Paper No. 8, US Government Printing Office, Washington, D.C., USA.
- Lindenmayer, D.B., P.J. Burton, and J.F. Franklin. 2008. Salvage logging and its ecological consequences. Island Press, Washington, D.C., USA.
- Lindenmayer, D.B., S. Thorn, and S. Banks. 2017. Please do not disturb ecosystems further. *Nature Ecology & Evolution* 1: 1–3.
- Lydersen, J.M., M.P. North, and B.M. Collins. 2014. Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. *Forest Ecology and Management* 328: 326–334. doi: [10.1016/j.foreco.2014.06.005](https://doi.org/10.1016/j.foreco.2014.06.005)
- Mallek, C., H. Safford, J. Viers, and J. Miller. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, USA. *Ecosphere* 4(12): 1–28. doi: [10.1890/ES13-00217.1](https://doi.org/10.1890/ES13-00217.1)
- Marcoux, H.M., L.D. Daniels, S.E. Gergel, E. Da Silva, Z. Gedalof, and P.F. Hessburg. 2015. Differentiating mixed- and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera. *Forest Ecology and Management* 341: 45–58. doi: [10.1016/j.foreco.2014.12.027](https://doi.org/10.1016/j.foreco.2014.12.027)
- Meyer, M.D. 2015. Forest fire severity patterns of resource objective wildfires in the southern Sierra Nevada. *Journal of Forestry* 113: 49–56. doi: [10.5849/jof.14-084](https://doi.org/10.5849/jof.14-084)
- Millar, C.I. 1996. Sierra Nevada Ecosystem Project. Sierra Nevada Ecosystem Project, Final Report to Congress, volume I. Assessment Summaries and Management Strategies, Centers for Water and Wildland Resources, Report No. 36, University of California, Davis, California, USA. Cooperative report of the USDA Pacific Southwest Research Station, Pacific Southwest Region, for the Sierra Nevada Framework Project, Sacramento, California, USA.
- Miller, J.D., and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* 109: 66–80. doi: [10.1016/j.rse.2006.12.006](https://doi.org/10.1016/j.rse.2006.12.006)
- Moen, C.A., and R.J. Gutiérrez. 1997. California spotted owl habitat selection in the central Sierra Nevada. *Journal of Wildlife Management* 61: 1281–1287. doi: [10.2307/3802127](https://doi.org/10.2307/3802127)
- Moritz, M.A., and S.G. Knowles. 2016. Coexisting with wildfire. *American Scientist* 104: 220–227. doi: [10.1511/2016.121.220](https://doi.org/10.1511/2016.121.220)

- Moritz, M.A., E. Batllori, R.A. Bradstock, A.M. Gill, J. Handmer, P.F. Hessburg, J. Leonard, S. McCaffrey, D.C. Odion, T. Schoennagel, and A.D. Syphard. 2014. Learning to coexist with wildfire. *Nature* 515: 58–66. doi: [10.1038/nature13946](https://doi.org/10.1038/nature13946)
- Noon, B.R., D. Murphy, S.R. Beissinger, M.L. Shaffer, and D.A. DellaSala. 2003. Conservation planning for US national forests: conducting comprehensive biodiversity assessments. *Bio-science* 53: 1217–1220. doi: [10.1641/0006-3568\(2003\)053\[1217:CPFUNF\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[1217:CPFUNF]2.0.CO;2)
- North, M., A. Brough, J. Long, B. Collins, P. Bowden, D. Yasuda, J. Miller, and N. Sugihara. 2015a. Constraints on mechanized treatment significantly limits mechanical fuels reduction extent in the Sierra Nevada. *Journal of Forestry* 113: 40–48. doi: [10.5849/jof.14-058](https://doi.org/10.5849/jof.14-058)
- North, M.P., S.L. Stephens, B.M. Collins, J.K. Agee, G. Aplet, J.F. Franklin, and P.Z. Fulé. 2015b. Reform forest fire management. *Science* 349: 1280–1281. doi: [10.1126/science.aab2356](https://doi.org/10.1126/science.aab2356)
- Odion, D.C., C.T. Hanson, A. Arsenault, W.L. Baker, D.A. DellaSala, R.L. Hutto, W. Klenner, M.A. Moritz, R.L. Sherriff, T.T. Veblen, and M.A. Williams. 2014. Examining historical and current mixed-severity fire regimes in ponderosa pine and mixed-conifer forests of western North America. *PLoS ONE* 9(2): e87852. doi: [10.1371/journal.pone.0087852](https://doi.org/10.1371/journal.pone.0087852)
- Odion, D.C., C.T. Hanson, W.L. Baker, D.A. DellaSala, and M.A. Williams. 2016. Areas of agreement and disagreement regarding ponderosa pine and mixed conifer forest fire regimes: a dialogue with Stevens *et al.* *PLoS ONE* 11: e0154579. doi: [10.1371/journal.pone.0154579](https://doi.org/10.1371/journal.pone.0154579)
- Parks, S.A., C. Miller, M.E. Parisien, L.M. Holsinger, S.Z. Dobrowski, and J. Abatzoglou. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere* 6(12): 1–13. doi: [10.1890/ES15-00294.1](https://doi.org/10.1890/ES15-00294.1)
- Perry, D.A., P.F. Hessburg, C.N. Skinner, T.A. Spies, S.L. Stephens, A.H. Taylor, J.F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and northern California. *Forest Ecology and Management* 262: 703–717. doi: [10.1016/j.foreco.2011.05.004](https://doi.org/10.1016/j.foreco.2011.05.004)
- Pimentel, D., L. Westra, and R.F. Noss, editors. 2000. *Ecological integrity: integrating environment, conservation and health*. Island Press, Washington, D.C., USA.
- Ricketts, T., E. Dinerstein, D. Olson, C. Loucks, W. Eichbaum, D. DellaSala, K. Kavanagh, P. Hedao, P. Hurley, K. Carney, R. Abell, and S. Walters. 1999. *A conservation assessment of the terrestrial ecoregions of North America*. Island Press, Washington, D.C., USA.
- Roberts, S.L. 2008. *The effects of fire on California spotted owls and their mammalian prey in the central Sierra Nevada, California*. Dissertation, University of California, Davis, USA.
- Roberts, S.L., J.W. van Wagtenonk, A.K. Miles, and D.A. Kelt. 2011. Effects of fire on spotted owl site occupancy in a late-successional forest. *Biological Conservation* 144: 610–619. doi: [10.1016/j.biocon.2010.11.002](https://doi.org/10.1016/j.biocon.2010.11.002)
- Rost, J., R.L. Hutto, L. Brotons, and P. Pons. 2013. Comparing the effect of salvage logging on birds in the Mediterranean Basin and the Rocky Mountains: common patterns, different conservation implications. *Biological Conservation* 158: 7–13. doi: [10.1016/j.biocon.2012.08.022](https://doi.org/10.1016/j.biocon.2012.08.022)
- Rota, C.T., J.J. Millspaugh, M.A. Rumble, C.P. Lehman, and D.C. Kesler. 2014. The role of wildfire, prescribed fire, and mountain pine beetle infestations on the population dynamics of black-backed woodpeckers in the Black Hills, South Dakota. *PLoS ONE* 9(4): e94700. doi: [10.1371/journal.pone.0094700](https://doi.org/10.1371/journal.pone.0094700)
- Saab, V.A., R.E. Russell, and J.G. Dudley. 2007. Nest densities of cavity-nesting birds in relation to postfire salvage logging and time since wildfire. *The Condor* 109: 97–108. doi: [10.1650/0010-5422\(2007\)109\[97:NDOCBI\]2.0.CO;2](https://doi.org/10.1650/0010-5422(2007)109[97:NDOCBI]2.0.CO;2)

- Saab, V.A., R.E. Russell, and J.G. Dudley. 2009. Nest-site selection by cavity-nesting birds in relation to postfire salvage logging. *Forest Ecology and Management* 257: 151–159. doi: [10.1016/j.foreco.2008.08.028](https://doi.org/10.1016/j.foreco.2008.08.028)
- Saracco, J.F., R.B. Siegel, and R.L. Wilkerson. 2011. Occupancy modeling of black-backed woodpeckers on burned Sierra Nevada forests. *Ecosphere* 2: 1–17. doi: [10.1890/ES10-00132.1](https://doi.org/10.1890/ES10-00132.1)
- Schoennagel, T., C.R. Nelson, D.M. Theobald, G.C. Carnwath, and T.B. Chapman. 2009. Implementation of national fire plan treatments near the wildland-urban interface in the western United States. *Proceedings National Academy of Sciences* 106: 10706–10711. doi: [10.1073/pnas.0900991106](https://doi.org/10.1073/pnas.0900991106)
- Schoennagel, T., and C.R. Nelson. 2011. Restoration relevance of recent national fire plan treatments in forests of the western United States. *Frontiers in Ecology and Environment* 9: 271–277. doi: [10.1890/090199](https://doi.org/10.1890/090199)
- Schoennagel, T., J.K. Balch, H. Brenkert-Smith, P.E. Dennison, B.J. Harvey, M.A. Krawchuk, N. Mietkiewicz, P. Morgan, M.A. Moritz, R. Rasker, M.G., Turner, and C. Whitlock. 2017. Adapt to more wildfire in western North American forests as climate changes. *PNAS* 114: 4582–4590. doi: [10.1073/pnas.1617464114](https://doi.org/10.1073/pnas.1617464114)
- Seavy, N.E., and J.D. Alexander. 2014. Songbird response to wildfire in mixed-conifer forest in south-western Oregon. *International Journal of Wildland Fire* 23: 246–258. doi: [10.1071/WF12081](https://doi.org/10.1071/WF12081)
- Siegel, R.B., M.W. Tingley, R.L. Wilkerson, C.A. Howell, M. Johnson, and P. Pyle. 2016. Age structure of black-backed woodpecker populations in burned forests. *Auk* 133: 69–78. doi: [10.1642/AUK-15-137.1](https://doi.org/10.1642/AUK-15-137.1)
- Stephens, S.L., J.M. Lydersen, B.M. Collins, D.L. Fry, and M.D. Meyer. 2015. Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the southern Sierra Nevada. *Ecosphere* 6(5): 1–63. doi: [10.1890/ES14-00379.1](https://doi.org/10.1890/ES14-00379.1)
- Stevens, J.T., H.D. Safford, M.P. North, J.S. Fried, A.N. Gray, P.M. Brown, C.R. Dolanc, S.Z. Dobrowski, D.A. Falk, C.A. Farris, J.F. Franklin, P.Z. Fulé, R.K. Hagmann, E.E. Knapp, J.D. Miller, D.F. Smith, T.W. Swetnam, and A.H. Taylor. 2016. Average stand age from forest inventory plots does not describe historical fire regimes in ponderosa pine and mixed-conifer forests of western North America. *PLoS ONE* 11(5): e0147688. doi: [10.1371/journal.pone.0147688](https://doi.org/10.1371/journal.pone.0147688)
- Swanson, M.E., J.F. Franklin, R.L. Beschta, C.M. Crisafulli, D.A. DellaSala, R.L. Hutto, D.B. Lindenmayer, and F.J. Swanson. 2011. The forgotten stage of forest succession: early-successional ecosystems on forested sites. *Frontiers in Ecology and Environment* 9: 117–125. doi: [10.1890/090157](https://doi.org/10.1890/090157)
- Thompson, J.R., T.A. Spies, and L.M. Ganio. 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. *PNAS* 104: 10743–10748. doi: [10.1073/pnas.0700229104](https://doi.org/10.1073/pnas.0700229104)
- Tingley, M.W., R.L. Wilkerson, M.L. Bond, C.A. Howell, and R.B. Siegel. 2014. Variation in home-range size of black-backed woodpeckers. *The Condor* 116: 325–340. doi: [10.1650/CONDOR-13-140.1](https://doi.org/10.1650/CONDOR-13-140.1)
- Tingley, M.W., V. Ruiz-Gutiérrez, R.L. Wilkerson, C.A. Howell, and R.B. Siegel. 2016. Pyrodiversity promotes avian diversity over the decade following forest fire. *Proceedings of the Royal Society B* 283: 20161703. doi: [10.1098/rspb.2016.1703](https://doi.org/10.1098/rspb.2016.1703)
- US Congress. 2003. HR 1904—Healthy Forest Restoration Act of 2003. Public Law number 108-148. <<https://www.congress.gov/bill/108th-congress/house-bill/1904>>. Accessed 4 May 2016.

- US Congress. 2015. HR 167—Wildfire Disaster Funding Act of 2015. <<https://www.congress.gov/bill/114th-congress/house-bill/167>>. Accessed 12 May 2017.
- USDA Forest Service. 2002. National fire plan. <http://www.fs.fed.us/database/budgetoffice/NFP_final32601.pdf>. Accessed 4 February 2017.
- USDA Forest Service. 2004. The Sierra Nevada Forest Plan Amendment (“Framework”), Final Environmental Impact Statement and Record of Decision. USDA Forest Service, Region 5, Vallejo, California, USA.
- USDA Forest Service. 2009. The National Strategy: the final phase in the development of the national cohesive wildland fire management strategy. <<https://www.forestsandrangelands.gov/strategy/thestrategy.shtml>>. Accessed 4 February 2017.
- USDA Forest Service. 2012. The forest planning rule. <<http://www.fs.usda.gov/planningrule>>. Accessed 4 February 2017.
- USDA Forest Service. 2014. Rim Fire Recovery Project, Final Environmental Impact Statement and Record of Decision. Stanislaus National Forest, Sonora, California, USA.
- USDA Forest Service. 2015. King Fire Restoration Project, Final Environmental Impact Statement and Record of Decision. Eldorado National Forest, Placerville, California, USA.
- USDA Forest Service. 2016. Revised Land and Resource Management Plans for the Sequoia, Sierra, and Inyo national forests, draft environmental impact statements. USDA Forest Service, Pacific Southwest Region, Vallejo, California, USA.
- USDI and USDA. 2014. The national strategy: the final phase of the development of the National Cohesive Wildland Fire Management Strategy (The National Strategy). US Department of the Interior and US Department of Agriculture, Washington, D.C., USA.
- Weatherspoon, C.P., S.J. Husari, and J.W. van Wagtenonk. 1992. Fire and fuels management in relation to owl habitat in forests of the Sierra Nevada and southern California. Pages 247–260 in: J. Verner, K.S. McKelvey, B.R. Noon, R.J. Gutiérrez, G.I. Gould, and T.W. Beck, technical coordinators. The California spotted owl: a technical assessment of its current status. General Technical Report PSW-133, US Forest Service, Pacific Southwest Research Station, Albany, California, USA.
- Williams, M.A., and W.L. Baker. 2012. Spatially extensive reconstructions show variable-severity fire and heterogeneous structure in historical western United States dry forests. *Global Ecology and Biogeography* 21: 1042–1052. doi: [10.1111/j.1466-8238.2011.00750.x](https://doi.org/10.1111/j.1466-8238.2011.00750.x)

Appendix 1. Fires affecting national forests and parks within the Sierra Nevada region, California, USA, from 1984 to 2014 based on the Monitoring Trends in Burn Severity project (<http://www.mtbs.gov>, accessed 8 September 2015). SD = standard deviation.

Management unit	Unit area hectares	Cumulative burned area		Mean fire size hectares (SD)	Largest fire area (ha) (% of fire occurring within management unit)
		Area (ha) (number of fires)	(%)		
Sequoia and Kings Canyon National Park	350 030	31 795 (34)	9.1	1 559 (1488)	3 806 (88.5)
Lassen Volcanic National Park	43 432	12 811 (9)	29.5	1 940 (3379)	6 383 (58.5)
Yosemite National Park	301 885	102 864 (49)	34.1	4 268 (15 174)	31 841 (30.6)
Eldorado National Forest	321 290	63 458 (9)	19.7	7 882 (12 496)	40 005 (99.6)
Inyo National Forest	834 535	47 767 (26)	5.7	4 536 (11 391)	7 995 (13.5)
Lake Tahoe Basin National Forest	80 595	1 138 (2)	1.4	1 423 (285.5)	1 083 (88.7)
Lassen National Forest	602 442	145 393 (46)	24.1	7 607 (10 801)	18 632 (75.0)
Modoc National Forest	818 852	85 022 (37)	10.4	3 221 (6 348)	15 507 (41.8)
Plumas National Forest	579 996	141 396 (37)	24.4	5 111 (8 112)	26 371 (99.0)
Sequoia National Forest	470 505	163 731 (61)	34.8	3 801 (8 563)	51 284 (86.5)
Sierra National Forest	574 583	48 785 (30)	8.5	3 261 (4373)	9 538 (100)
Stanislaus National Forest	441 366	171 391 (35)	38.8	7 647 (17 908)	71 614 (68.8)
Tahoe National Forest	476 706	54 294 (19)	11.4	5 786 (9640)	8 394 (100)
Toiyabe National Forest	731 467	63 715 (33)	8.7	2 797 (3 692)	10 163 (100)

Appendix 2. Wilderness and adjacent inventoried roadless areas (IRA) in the Sierra Nevada region, California, USA, compared to largest fire sizes.

Wilderness/IRA complex	Complex size (ha)	Largest fire within associated forest unit¹ (1984 to 2014)
Eldorado	75 255	40 005
Inyo	601 756	7 995
Lassen	99 821	6 383
Modoc	109 725	15 507
Plumas	35 987	26 371
Sequoia	266 316	51 284
Sierra	293 314	9 538
Stanislaus	143 319	71 614
Tahoe	69 519	8 394
Toiyabe	348 597	10 163
Lake Tahoe Basin	28 345	1 083

¹ Fire sizes are for national forest units with wilderness/IRA complexes. Many fires extend beyond national forest and wilderness/IRA boundaries (see Appendix 1).